APTUS : Applications for Tether United Satellites

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Abstract. Two ten centimeter cube micro-satellites will be built at the W.R.Woolrich Laboratories at the University of Texas at Austin for the purpose of providing visual data regarding the changing density of the Earth's atmosphere at low earth orbit altitudes, and investigating the ability of electro-dynamic tethers to change the orbital altitude of a small satellite. The cubes will be tethered together via a highly reflective Aracon fiber that will be approximately three kilometers in length. The cubes will separate after orbit deployment, placing the tether in tension. The tether will reflect sunlight as it passes over the Earth, making it visible without the use of telescopes or binoculars when the cubes are at an altitude of roughly 300 kilometers. The tether will then detach from one cube, allowing it to hang freely from the other cube. At this point, it will be subject to atmospheric drag that will cause the tether to deform. The deformation and shape of the tether are directly correlated to the atmospheric density, and although there are other forces acting on the tether, these are assumed to be well known. An internet based data recording system will be established, where observers from anywhere in the world can send visual data of the tether along with the observation time, azimuth and elevation of the satellite, and the latitude and longitude of the observer's locations. These data will then be used to create a model of the density of the Earth's atmosphere at low earth orbit altitude.
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INTRODUCTION

The University of Texas at Austin Aerospace Engineering department is currently working on a project called Application for Tether United Satellites, or APTUS. This project involves cooperation with several other educational and industrial entities, including Stanford University, California Polytechnic Institute, and One Stop Satellite Solutions. The APTUS project concentrates on creation of an atmospheric density model, as well as testing of space tether electro-dynamic properties.

Atmospheric Density Model

Atmospheric density models for the Earth are of primary importance to organizations that build spacecraft, because they supply engineers with an estimate of the level of atmospheric drag that is likely to be acting on their satellite during its mission, which influences the spacecraft and mission design. There are currently several atmospheric density models for the Earth; however, these models could be improved through collection and incorporation of visual data from a free-flying tether experiment, the primary goal of the APTUS project.

Inaccuracies with the current models are due in part to the fact that the atmosphere at low altitudes is partially comprised of plasma. An accurate mathematical model of atmospheric plasma has yet to be created, and the effects that plasma has on spacecraft are not well understood. This is most likely because it only exists in space and therefore, humans have had almost no contact with it. Another complication that scientists face when trying to create an accurate model is that the Earth's density varies with position over the Earth, altitude and time of day, which makes a mathematical model very complicated. Atmospheric density can be directly correlated to solar effects, and so the density at a point changes drastically as the atmosphere at that point moves from daylight to being in the Earth's shadow.

Engineers encounter extreme difficulty when faced with the challenge of creating an accurate model through mathematical analysis of the atmosphere alone. Data regarding the atmospheric density need to be gathered from more direct measurements in order to create a more accurate model.

The primary purpose for this mission will be to place a tether into orbit, attached to a small satellite, and record data on the shape the tether takes as it passes through the Earth's atmosphere. The tether will be deformed from a straight line into different shapes due to the varying atmospheric drag acting on different points along the length of the tether. Atmospheric drag is directly dependent on atmospheric density, so by observing the shape of the tether, one can judge the relative magnitude of the atmospheric density acting on different points along its length. This coupled with an accurate mathematical and/or computational model of the deformation of a filament or a tether in a resisting medium will be used to recover that atmospheric density

model at the time and location the actual tether was observed. This description of this model is outside the scope of this paper and will be addressed at a later time.

One of the most exciting aspects of the ATPUS project is that once the tether reaches an altitude of roughly 300 km, it will be visible from the earth with the naked eye at optimal viewing times such as dusk and dawn, because it will be reflecting sunlight. Data regarding the shape of the tether will be gathered by taking pictures of the satellite and tether as they pass over an observer's location. To create an accurate model, the APTUS project will require cooperation with people from around the world in the data collection process due to the fact that the tether needs to be observed at different locations around the world, as well as different orbital altitudes and times of day. The easy viewing conditions of the tether allow for a wider range of people to participate in a space-related project, including those with no access to telescopes or other visual aids. Another promising aspect of the APTUS project is that including normal, every-day people ranging from children to adults all around the world in the data collection method will increase general interest in space for people who were previously apathetic or unmotivated about space exploration and its applications.

Tether Electro-Dynamics

Placing a tether into orbit around the Earth requires the use of a tethered spacecraft, or a tether united satellite design. In order to accomplish the task of placing two tethered spacecraft into orbit, the University of Texas at Austin will take part in a program called CubeSat, which was created by Professor Robert Twiggs at Stanford University. CubeSat is a joint project between Stanford University, California Polytechnic Institute, and One Stop Satellite Solutions, and is aimed at providing opportunities for low cost launch

of student built satellites. A representation of CubeSats in orbit can be seen in Figure 1.
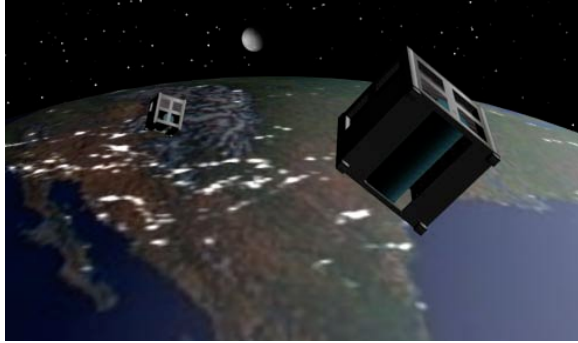
Figure 1 - CubeSats in Earth Orbit

Participation in the CubeSat program requires that the APTUS team launch their satellite along with the other participating CubeSat teams into an orbital altitude of roughly 650km. Given this initial altitude, calculations show that the tether and satellite would not de-orbit to the data collection altitude of 300 km for a minimum of several decades. Obviously, this time span is not optimal for success of the mission because in order to involve people around the world in the project, a great public interest must be generated. If the participants were forced to wait for decades, public interest would wane, and the accuracy of the data and final model would be compromised. Therefore, a lightweight, cost-effective de-orbiting method must be created.

The tether electro-dynamic properties will be used to de-orbit the satellite and tether from 650km to 300km in a matter of months. As the tether passes through the Earth's atmosphere, it also passes through the Earth's magnetic field. By passing an electric current through this tether as it moves through the magnetic field of the Earth, a force will be created on the tether that will push it and in turn the connected satellite towards the Earth. This method is based on the equation[1]

$$\mathbf{F} = q\mathbf{v} \times \mathbf{B} \qquad [1]$$

where $\mathbf{F}$ is the resultant force acting on the tether, q is the charge of the current, $\mathbf{v}$ is the vector velocity of the tether in orbit, and $\mathbf{B}$ is the magnetic field vector of the Earth.[1] A representation of the forces acting on the tether as it passes electrical current along its length and moves through the magnetic field can be seen in Figure 2.
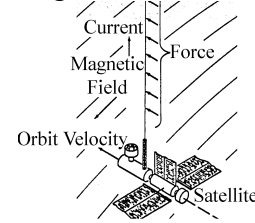
Figure 2 - Forces Acting on Electro-Dynamic Tether Moving Through Magnetic Field [2]

When a positive current is passed from the satellite to the tether, and the charged particles moving through the tether are allowed to come into contact with the magnetic field, a distributed load along the tether results. This load increases the acceleration and orbital velocity of the tether satellite system, thereby decreasing the semi-major axis. The equation relating the semi-major axis of the orbit to tether electro-dynamic properties is

$$\Delta a \approx \cos(l) \frac{kl}{m} \int I dt \qquad [2]$$

where a is the semi-major axis, l is the length of the tether, m is the mass of the tether-satellite system, I is the current passed through the tether, and t is time. Calculation of this equation shows that passing a 5 amp current through the tether will cause the satellite to de-orbit from 650km to 300km in three to six months.[3]

Reversing the charge of the particles passing through the tether to negative will cause an "orbit boost" of the satellite, in which the satellite orbital altitude or semi-major axis increases. Orbital boosts of very short duration can help to keep the satellite at an altitude suitable for data collection, if they are executed after the satellite has reached a 300km altitude. By keeping the satellite around 300km, the data collection phase of the project can be extended, allowing for more

plentiful and precise data. Also, the longer the tether remains visible, the more public interest in the project will be generated.

Overview

This paper will continue with the APTUS Physical Layout section, which will give a description of all subsystems on both the communications and payload cubes as well as their pre-launch configurations and a description of how the cubes will be integrated with the P-POD deployer. Next, the APTUS Operations Description section will present an in-depth sequence of events for the mission. Finally, the conclusion section will summarize all of the important aspects of the project and the primary issues of the paper.

APTUS PHYSICAL LAYOUT

This section addresses the design and function of each subsystem on board both the payload and communications cubes. It also addresses the location of all subsystems in the cubes as well as the integration of the communications and payload cubes with the P-POD deployer.

Subsystems Description

This section outlines the descriptions of the subsystems on board both cubes, including the connections between components and subsystem function flow charts.

Power

The subsystems on board the payload cube do not require a regenerating power source; therefore the power subsystem on board the payload cube will consist solely of non-rechargeable batteries. The batteries will be connected to the accelerometer board, which will serve as the Central Processing Unit (CPU) for the payload cube. The accelerometer will in turn be connected to an external circuit switch. The switch will initially be in the open position, ensuring that

the other subsystems are powered down during launch, deployment, and separation from the primary payload. When the internal timer on the accelerometer reaches a pre-specified time after deployment, it will instruct the switch to close, sending power to the separation and tether/spool subsystems. Use of a timer is required because the CubeSats need to move away from the primary payload to a specified distance before powering up their subsystems so that the CubeSat subsystems do not interfere with the primary payload systems. A representation of the power subsystem for the payload cube is shown in Figure 3.
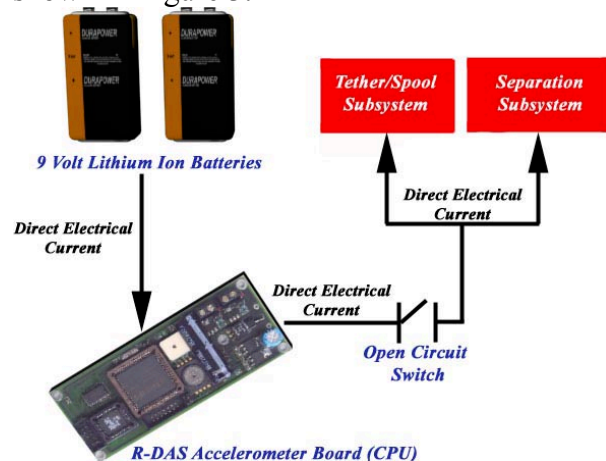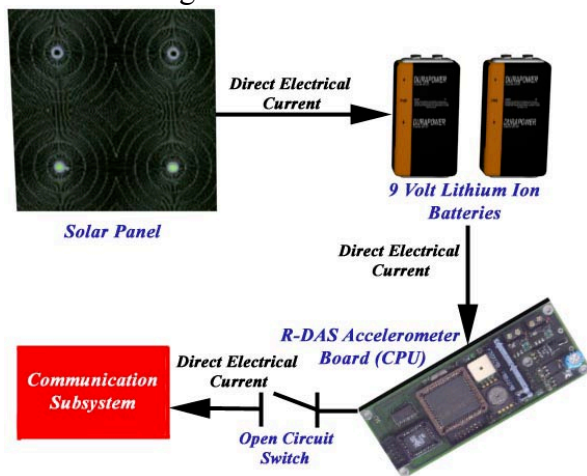

Figure 3 - Payload Cube Power Subsystem Flowchart

The power subsystem onboard the communications cube will be comprised of both batteries and solar panels. Solar panels are required on the communications cube because the communications subsystem will need to function constantly throughout the mission, and this requires the use of a recharging power source. The solar panels will include solar cells and will continuously recharge the batteries while the cube is in sunlight. The stored energy in the batteries will power the communication subsystem while the cube is in darkness. The solar panels will be connected via an electrical circuit to the batteries, supplying them with DC electrical current. The batteries will then be connected to the accelerometer, and

electrical circuit switch in the same manner as the payload cube. The accelerometer on board the communications cube also functions as the CPU for that satellite. The switch on the communications cube should close at the same time as the switch on the payload cube. When the switch closes on the communications system, the communications subsystem will be powered up. A representation of the power subsystem onboard the communications cube is shown in Figure 4.

Figure 4 - Communications Cube Power Subsystem Flowchart

Communications

The communications subsystem will be comprised of four main components, including a GPS receiver, a transmitter, an adapter and an antenna. The GPS receiver will accumulate data on the location of the cube with respect to the Earth, and will then send an NMEA GPS signal to the adapter. The GPS signal leaving the receiver is not compatible with the required input for the transceiver, which is NFM of F3E, so the adapter will alter the signal from GPS NMEA into one of these forms. The transceiver will then send a HAM frequency signal via the antenna to a commercial or amateur HAM radio satellite in orbit. The commercial satellite will have a much broader bandwidth, and will be able to send the CubeSat signal down to a ground station much more easily than the CubeSat itself could. The UT CubeSat team will acquire the HAM signal as the commercial satellite sends it down, giving the location of the CubeSat in orbit. A representation of the communications subsystem is shown in Figure 5.
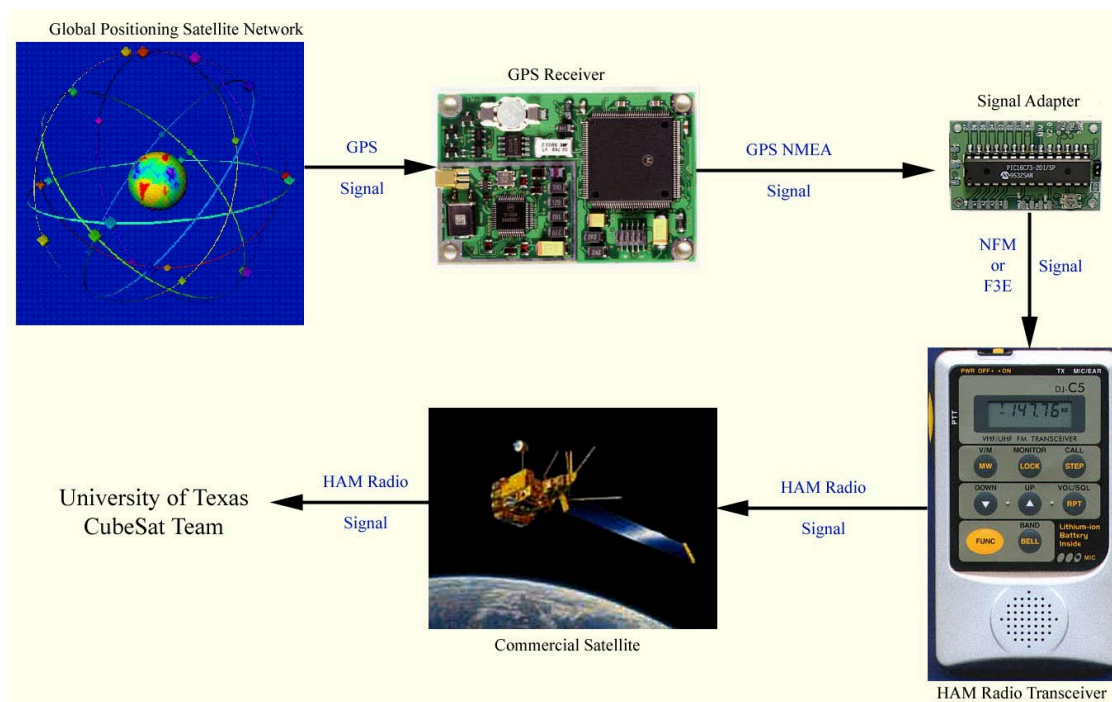
Figure 5 – Communication Subsystem Flowchart

Tether/Spool

The tether will be wrapped around a spool that resembles the reels found in fishing equipment. The spool will be locked in place before flight, and will not be unlocked until after the cubes have moved away from the primary payload far enough to power up the subsystems. The subsystem will be unlocked by passing current through a solenoid, which will cut the mechanism holding the lock in place. The CubeSats will not have significant relative velocity after they are deployed from the P-POD deployer, so they will not separate until the separation subsystem is activated. Therefore, the tether will not experience any undue stress between deployment and power-up of the subsystems, even though the spool is locked and the tether is not able to extend between the cubes.

The tether is partially made of metal, which enables the tether to be used as an antenna. This design eliminates the need for a more complicated antenna deployment procedure, and conserves space that would have been used to house the extra antenna.

When the subsystems are powered up and the tether is free to unreel and extend between the two cubes, the communications cube will simply pull the tether from the spool as the cubes separate. This design eliminates the need for a motor to force the reel to expel the tether, which simplifies the design, however it also requires the development of a separation procedure.

Separation

The separation subsystem is comprised of a spring-loaded parachute that will be housed in the Payload cube, opposite the side on which the reel is located. The tether and parachute are designed to deploy in opposite directions. The parachute will be packed inside a lightweight carbon composite box with one face open so that the parachute can be deployed from the box upon initiation of the separation procedure. A representation of the parachute inside the carbon composite box can be seen in Figure 6.
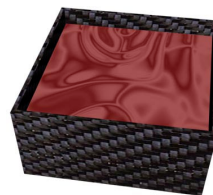
**Figure 6 - Parachute Packed Inside Carbon Composite Box**

Pre-Launch Configuration

The Pre-launch configuration will include the physical layout of the payload cube, the communications cube, and the integration of both cubes inside the P-POD deployer. The physical layout of the communications cube will be a set of shelves onto which the components will be mounted. The shelves can be inserted in a layer form into the communications cube.

Payload Cube

The payload cube will include three main subsystems, including power, tether/spool and separation. The power subsystem will be comprised of batteries and will be located in the center area of the cube. The tether/spool and separation subsystems will be located on opposite sides of the cube, both close to the external surface of the cube, due to the fact that they will both require interaction with the area immediately outside of the cube. The CubeSat program requires that the payload cube and the communications cube hold a kill switch and a timer. The kill switch will be attached to the top corner of both cubes, and the accelerometer will be located directly behind the front wall, so as to allow for easy integration between it and the flight pin. The

flight pin must be inserted in order to insure that all systems are powered down. A representation of the fully constructed payload cube is shown in Figure 7.
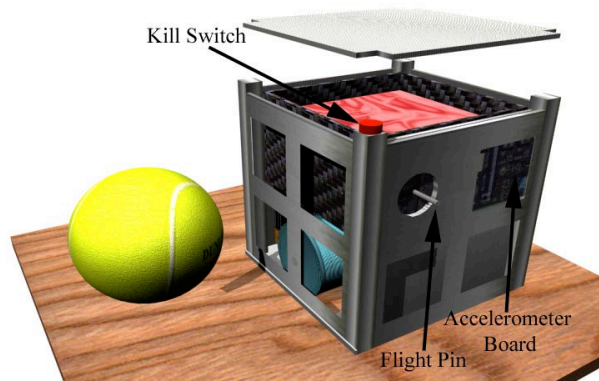
**Figure 7 - Fully Constructed Payload Cube**

Communications Cube

The communications cube will hold two subsystems, including power and communications. A kill switch and timer will also be included in the physical layout of the communications cube. The solar panels will be located on all six sides of the communications cube to insure that at least one solar panel will be facing the sun, because there will be no attitude control on either cube. On one face of the cube, the panels will have to be arranged around some small opening, so that access to the main internal structure of the cube is provided. At this small opening, the tether will be permanently attached to the internal structure of the communications cube.

Integration with the Poly Picosatellite Orbital Deployer

The Poly Picosatellite Orbital Deployer (P-POD) is a spring-loaded launching device designed and built by California Polytechnic Institute for the specific purpose of placing the CubeSats into orbit. It will be permanently attached to payload interface of the final stage of the launch vehicle. The P-POD and the CubeSats are not the primary payload for

launch aboard the Russian rocket. The primary payload will be a commercial satellite. A representation of the P-POD deployer and the CubeSats it will be launching can be seen in Figure 8.
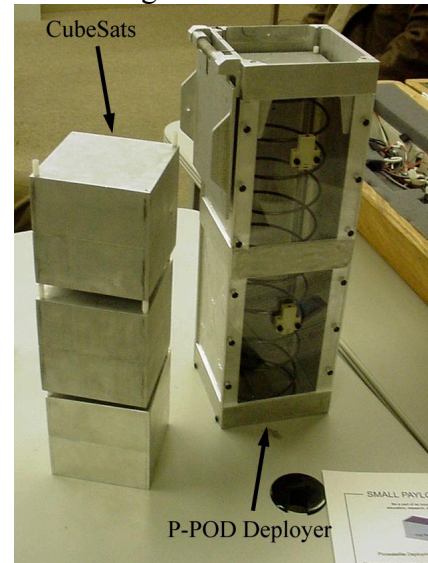
Figure 8 - P-POD Deployer with CubeSats [4]

When the CubeSats are placed inside the P-POD deployer, the kill switch will be pressed against the sidewall of the deployer, which will press the switch into the structure of the CubeSat. When the kill switch is depressed into the Cube, it becomes activated, and this ensures that all subsystems are powered down during launch. As the cubes exit the P-POD deployer upon ejection, the kill switch, which is spring loaded, pops back out of the structure, and triggers the internal timer on the accelerometer board.

APTUS OPERATIONS DESCRIPTION

The operations description of the APTUS mission includes an in depth sequence of events for the mission.

Sequence of Events

The sequence of events outlines the milestone events of the mission beginning with launch of the CubeSats with the P-POD deployer and

the primary payload and ending with the creation of an atmospheric density model.

1. Launch

Launch will take place aboard a Russian rocket in November of 2002.

2. Primary Payload Deployment

A commercial satellite will be the primary payload, and the P-POD deployer will be "piggy-backed" onto the last stage of the launch vehicle.

3. P-POD Deployment

The P-POD will eject three CubeSats at a time into an orbit of around 650 km above the surface of the Earth at an inclination of 85°. A representation of P-POD deployment is shown in Figure 9.
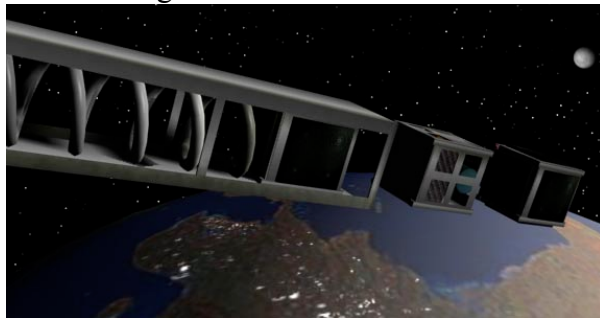
Figure 9 - P-POD Deployment

4. Kill Switch Deactivation

When the kill switches are depressed into the CubeSat structures, they will serve as a means of opening the circuit between the battery and the accelerometers. As the CubeSats exit the P-POD structure, the spring loaded kill switches will pop out from inside the CubeSat structures, deactivating the power shutdown, closing the circuits between the batteries and the accelerometers, and starting the accelerometer internal timers.

5. Timer Starts

When the kill switches are deactivated, the batteries will begin running current into the accelerometers. During the period in which the CubeSats are separating from the primary payload to a distance where the CubeSats can safely power up all subsystems without causing adverse effects aboard the primary payload, the internal accelerometer timers will keep the circuits between the batteries and the subsystems onboard both cubes open. By keeping these circuits open, the accelerometers are ensuring that no power is supplied to the subsystems until the timers run out.

6. Subsystems Power Up

When the timers run out, the circuit between the batteries and all subsystems requiring onboard power will be closed. Onboard the Payload cube, the power, tether/spool, and separation subsystems will be activated, and the power and communications subsystems will be activated onboard the communications cube. Although the tether/spool and separation subsystems do not require continuous power, some battery power will be required in order to unlock the spool, allowing it to rotate freely, and to deploy the parachute in the separation subsystem.

7. Subsystems Functioning

When all subsystems are functioning, the communications cube will immediately begin transmitting the GPS data in the form of a HAM radio signal through the antenna to a commercial or amateur HAM radio satellite, then down to an Earth ground station, and the Payload cube will deploy the parachute, beginning the separation procedure.

8. Separation

When the parachute is deployed, it will eventually inflate, increasing the surface area

of the payload cube by a factor of ten. Increased atmospheric drag will immediately begin decelerating the payload cube. As the payload cube decelerates, it will steadily separate from the communications cube, which will pull the tether from the spool. A representation of the separation procedure can be seen in Figure 10.
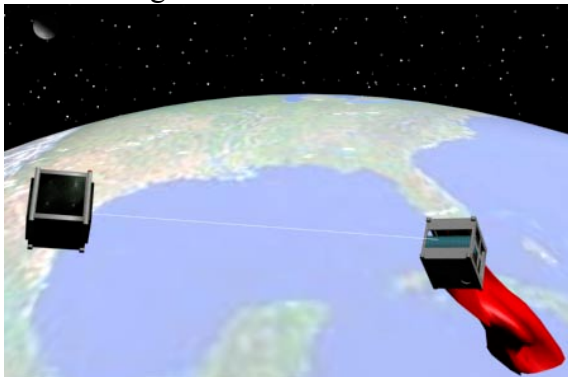

Figure 10 - Separation Stage

9. Tether Detaches from Payload Cube

The tether will not be permanently attached to either the spool or the Payload cube structure. When the spool runs out of tether, the tether will simply detach from the payload cube, and the two will begin separating.

10. Tether Drags Behind Communications Cube

After the tether disconnects from the payload cube and begins to separate from it, the tether will still be permanently attached to the communications cube. The tether will then drag behind the communications cube as it slowly re-enters the Earth's atmosphere.

11. Electro-Dynamic Tether De-Orbit Maneuver

The power subsystem onboard the communications cube will pass a positive current through the tether. This current will interact with the magnetic field of the Earth to create a downward force on the tether, causing

both the tether and the communications cube to de-orbit more quickly.

12. Communications Cube Reaches 300 km Altitude

Once the Communications cube descends to an altitude of roughly 300 km, the tether will become visible from Earth with the naked eye. A representation of what the tether will look like from the Earth can be seen in Figure 11.
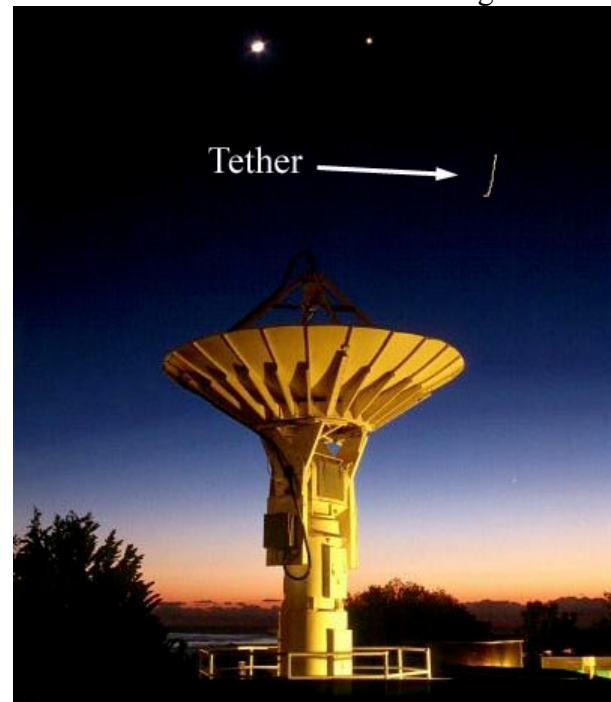

Figure 11 - Visible Tether in the Evening Sky

13. Electro-Dynamic Tether Orbit Boost Maneuver

The power subsystem onboard the communications cube will pass a negative current through the tether, which will create an upward force on the tether, causing both the tether and communications cube to complete an orbit boost. Several orbit boosts will be initiated by the pre-programmed accelerometer to keep the tether at the optimal data collection altitude of 300km for an extended period of time.

14. Data Recording

Data recording can begin as soon as the tether becomes visible with the naked eye. People from all around the world will take photographs, digital pictures or videotape of the tether as it passes over their location.

15. Data Sent to UT

Once the data has been collected, it will be sent to the University of Texas at Austin via an Internet based data recording system.

16. Re-Entry of Both cubes

When data collection has been concluded, both cubes and the tether will re-enter the Earth's atmosphere, where they will be incinerated. The destruction of all three items guarantees that the APTUS project will not add to the already complicated space debris problem.

17. UT Creates Model

Once all data has been recorded and the University of Texas has received them, students will create an atmospheric density model.

CONCLUSION

The APTUS project addresses two exciting and innovative applications of tether united satellite design. First, it involves increasing the accuracy of existing atmospheric density models by placing a tether into orbit, then gathering data on the shape of the tether in orbit and incorporating the data into current models. The shape of the tether depends on the atmospheric drag acting on the tether, which is directly correlated to atmospheric density. Secondly, the project takes advantage of the electro-dynamic properties of the tether by completing a low-cost, lightweight orbit boost and rapid de-orbit of the communications cube by passing current through the tether and allowing the charged electrons to interact with the magnetic field of the Earth.

The APTUS project incorporates the cutting edge technology of tether electro-dynamics as well as an innovative solution to the inaccuracy of the current atmospheric density model. Future tasks will include the development of computer simulations to validate and test both the behavior of the tether in LEO and its capability to de-boost or re-boost a satellite's orbit.

Also, the University of Texas CubeSat Team aims to involve people from all around the world, of all ages, as well as of different cultural and socio-economic backgrounds in the data collection process. Including the public in the project will increase public interest in space science and exploration. The APTUS project will yield valuable scientific results and the priceless benefit of inspiring young and old alike to explore their surroundings.

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